USAARL Report No. 95-14

Luminance Effects on Visual Acuity and Small Letter Contrast Sensitivity

(Reprint)

By

Jeff Rabin

Aircrew Health and Performance Division

February 1995

United States Army Aeromedical Research Laboratory
Fort Rucker, Alabama 36362-0577

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) USAARL Report 95-14	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Aeromedical Research Laboratory 6b. OFFICE SYMBOL (If applicable) MCMR-UAS-VS	7a. NAME OF MONITORING ORGANIZATION U.S. Army Medical Research and Materiel Command
6c. ADDRESS (City, State, and ZIP Code) P.O. Box 620577 Ft. Rucker, AL 36362-0577	7b. ADDRESS (City, State, and ZIP Code) Fort Detrick Frederick, MD 21702-5012
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8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62787A	3016278 7A879	PE	164

11. TITLE (Include Security Classification)

Luminance Effects on Visual Acuity and Small Letter Contrast Sensitivity

12. PERSONAL AUTHOR(S)
Jeff Rabin

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM ____ TO ____	1995 February	4

16. SUPPLEMENTARY NOTATION

Printed in Optometry and Vision Science, 1994, Vol. 71, No. 11, pp. 685-688

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
06	04	
20	06	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Visual acuity, Contrast sensitivity, luminance, resolution

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The purpose of this study was to evaluate the effects of luminance on visual acuity (VA) and small letter contrast sensitivity (SLCS). Computer-generated letter charts were used to measure VA and SLCS [6/7.5 (20/25) Snellen equivalent] as a function of stimulus luminance. Letter size (VA) and contrast (SLCS) were varied in equal logarithmic steps, making the task and scoring procedure comparable for the two types of measurement. Both VA and SLCS decreased with decreasing luminance, but the effect was far greater in the contrast domain. Reducing luminance from 116 cd/m^2 to 0.23 cd/m^2 produced a 3 x reduction in VA, but a 17 x reduction in SLCS. The greater sensitivity of SLCS to luminance endured even after correction for greater measurement variability. SLCS is a sensitive approach for detecting resolution loss undisclosed by standard measures of VA. It may be useful for monitoring visual loss from light attenuation in early cataracts, and for detecting subtle resolution loss from neural or pathologic factors in ocular and neuro-ophthalmologic disease.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Chief, Scientific Information Center	22b. TELEPHONE (Include Area Code) (334) 255-6907 22c. OFFICE SYMBOL MCMR-UAX-SS

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

1040-5488/94/7111-0685$03.00/0
OPTOMETRY AND VISION SCIENCE

Vol. 71, No. 11, pp. 685–688

Luminance Effects on Visual Acuity and Small Letter Contrast Sensitivity

JEFF RABIN*
Aircrew Health and Performance Division, U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama

ABSTRACT

The purpose of this study was to evaluate the effects of luminance on visual acuity (VA) and small letter contrast sensitivity (SLCS). Computer-generated letter charts were used to measure VA and SLCS [6/7.5 (20/25) Snellen equivalent] as a function of stimulus luminance. Letter size (VA) and contrast (SLCS) were varied in equal logarithmic steps, making the task and scoring procedure comparable for the two types of measurement. Both VA and SLCS decreased with decreasing luminance, but the effect was far greater in the contrast domain. Reducing luminance from 116 cd/m^2 to 0.23 cd/m^2 produced a 3 × reduction in VA, but a 17 × reduction in SLCS. The greater sensitivity of SLCS to luminance endured even after correction for greater measurement variability. SLCS is a sensitive approach for detecting resolution loss undisclosed by standard measures of VA. It may be useful for monitoring visual loss from light attenuation in early cataracts, and for detecting subtle resolution loss from neural or pathologic factors in ocular and neuro-ophthalmologic disease.

Key Words: visual acuity, contrast sensitivity, luminance, resolution

A number of visual functions, including visual acuity (VA),[1–4] contrast sensitivity (CS),[5–8] and temporal aspects of vision,[9] are dependent on the luminance of the visual stimulus. Typically, the relation between vision and luminance is expressed in terms of the effects on VA. Although decreasing luminance causes a reduction in VA, clinically significant loss of VA does not occur with luminance reductions over much of the photopic range.[3] Often it is tacitly assumed that resolution is normal under moderate to high light levels, but is reduced under lower levels of illumination.

CS also decreases with decreasing stimulus luminance.[5–8] However, because CS typically is measured with moderate spatial frequency stimuli, comparison of CS to VA loss with decreasing luminance is problematic inasmuch as the two measures involve separate mechanisms affected differently by optical and neural factors. Comparison of luminance-related resolution loss between acuity and contrast domains requires stimuli of comparable size.

Recently it was demonstrated that small letter CS (SLCS) is a more sensitive index of defocus than conventional measures of VA.[10] Like VA, SLCS is measured with small letters containing higher spatial frequencies, but the letters are varied in contrast rather than in size. The greater sensitivity of SLCS to defocus is attributed to the steep, descending slope of the CS function for which small changes in VA are associated with larger changes in CS. This concept is illustrated in Fig. 1, which shows that defocus shifts the descending limb of the CS function downward and to the left. The leftward shift along the spatial frequency axis represents the loss of VA. The downward shift along the contrast dimension shows the relatively greater loss of SLCS.

If reducing the luminance of the stimulus affects the CS function in a manner similar to the effects of defocus, then SLCS may prove to be more sensitive than VA to subtle reductions in

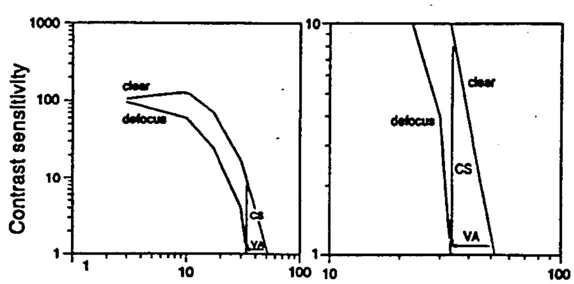

Figure 1. Defocus effects on VA and CS. The left panel shows the CS function with and without defocus, whereas the right panel shows a magnified view of the descending limb. Defocus reduces the contrast of higher spatial frequencies shifting the CS function downward and, consequently, to the left. Because of the steep slope of the descending limb, a reduction in VA is associated with a greater loss of CS, as indicated by the arrow lengths. A similar effect occurs with luminance-induced changes in resolution.

Received February 9, 1994; revision received September 20, 1994.
*O.D., Ph.D.

stimulus luminance. This could have clinical application in that visual loss from light attenuation with early cataracts may be better detected with SLCS. This report compares the effects of luminance reduction on VA to its effects on SLCS. Theoretical factors and clinical applications are considered.

METHODS

VA and SLCS were measured with computer-generated letter charts displayed on a video monitor. Monitor luminance and letter contrast were under software control. The VA and SLCS charts were patterned after those developed by Bailey and Lovie[11] and Pelli et al.,[12] respectively. Each chart consisted of seven rows of letters with five letters per row, and subtended a horizontal visual angle of 3.1°. Two video frames were required to display the entire range of contrasts on the SLCS chart. The VA chart consisted of black, high contrast (93%) letters on a white background. The letters were larger on top, and became progressively smaller, by line, in 0.1 log unit steps with VA ranging from 6/15.1 (20/50.2) to 6/3.8 (20/12.6) (0.4 to -0.2 logMAR). The same principles were used to design the SLCS chart, but letter size was held constant (6/7.5 or 20/25 Snellen equivalent), whereas contrast decreased, by line, in 0.1 log unit steps (from 93% to 5%). As noted in the earlier text, small letters were used to measure CS to: (1) assess high spatial frequency channels like those used for VA, and (2) take advantage of the steep slope of the CS function for which small changes in VA are associated with larger changes in CS (Fig. 1). The same letters were used on both charts [5 × 4 aspect ratio (height × width) non-serifed letters of about equal visibility[11]], but letter sequence was varied from trial to trial by software control to discourage learning effects. The charts were presented at white background luminances ranging from 0.23 cd/m^2 to 116 cd/m^2 in 0.3 log unit (2×) steps. The different luminances were achieved by placing neutral filters of appropriate optical density in a filter holder directly in front of the subject's eye. Values were specified in terms of the luminance of the white background because it occupied most of the display and probably governed the adaptational state of the eye.[a] The luminances were presented in ascending order to minimize the time required for adaptation, and to discourage learning effects because resolution improves with luminance.

[a] Because mean luminance on a variable contrast chart increases with decreasing contrast (lower contrast letters have higher mean luminance), this variability could influence our results. To explore this possibility, VA and SLCS also were evaluated as a function of the mean luminance of the letter row at which threshold occurred. Results were essentially the same when expressed relative to mean luminance as they were when expressed relative to background luminance.

Subjects were seated 4.8 m from the display in an otherwise dark room. The left eye was occluded with an eye patch, and the subject adapted with the right eye for 6 min to a uniform field displayed on the monitor at the lowest luminance tested (0.23 cd/m^2). This period of adaptation was deemed sufficient because longer periods produced no improvement in VA or SLCS. After adaptation, the VA chart was displayed, and the subject was instructed to start from the top and read each row of the chart as far down as possible. This was followed by SLCS testing. The subject then adapted for 1 min to a uniform field at the next highest luminance followed by measurement of VA and SLCS. This procedure was continued across the entire range of luminances. Scoring was conducted by letter with a precision of 0.02 log units.

VA and SLCS thresholds were obtained from 5 subjects (ages 22 to 39 years). Each subject was refracted to maximum VA and optically corrected during testing. Informed consent was obtained from all subjects after protocol approval by our institutional review committee.

RESULTS

Fig. 2 shows mean (±1 SE) VA (left) and SLCS (right) plotted as a function of stimulus luminance. By displaying the results on scales that span equivalent logarithmic ranges, the magnitude of the effect can be compared directly between acuity and contrast domains. Both VA and SLCS improve with increasing luminance, a finding that is well established from previous studies. However, the magnitude of this effect is far greater in the contrast domain (Friedman nonparametric two-way analysis of variance, $\chi^2 = 16$, $p < 0.001$). Increasing the luminance from 0.23 to 116 cd/m^2 produces a 3× increase in VA, but a 17× increase in SLCS. With each 2× increase in luminance, VA increases 10%, an improvement of two letters on the acuity chart, whereas SLCS

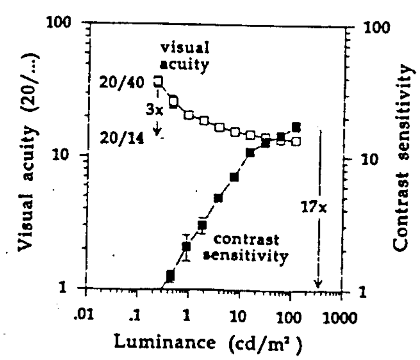

Figure 2. Mean (±1 SE) VA and SLCS (20/25 letter size) are plotted against the luminance of the letter chart. Values are shown on logarithmic axes which span equivalent ranges (100× change in visual threshold). For the range of luminances tested, VA changes 3×, whereas SLCS changes 17× (20/40 = 6/12 and 20/14 = 6/4.2).

increases 40%, an improvement of 1½ lines on the contrast chart.

Although changes in luminance have a greater impact on SLCS than on VA, the significance of this finding depends on the variability of the measurement. A larger effect does not ensure greater sensitivity if the measurement is more variable, as is the case for SLCS. To standardize measurements with respect to variability, the difference between each visual threshold and the mean threshold at maximum luminance was divided by the standard deviation (SD) of the measurement. This transformation, which specifies all scores as SD's from the mean, allows for direct comparison of VA and SLCS results. Means and SD's (logMAR: -0.15 ± 0.05; logCS: 1.20 ± 0.08) were from a previous study,[10] which used a larger sample size that better approximated a normal distribution. Fig. 3 shows the average number of SD's from the mean (at 116 cd/m^2) plotted against luminance for VA and SLCS. Using a conservative criterion of 3 SD's from the mean performance at maximum luminance (116 cd/m^2), SLCS is significantly reduced at 10 cd/m^2, whereas VA is not significantly reduced until the luminance is decreased to 1 cd/m^2, a 10× lower luminance. Thus, even when correction is made for variability, SLCS still provides a more sensitive index of subtle changes in the luminance of the visual stimulus, and this effect is highly significant (Friedman two-way analysis of variance, $\chi^2 = 18$, $p < 0.001$).

Despite the larger reduction in SLCS with decreasing luminance, the origin of this effect remains unclear. Although optical factors, such as pupil dilation and increased accommodation (night myopia), contribute to the reduction in vision with decreasing luminance, research suggests that these effects are most detrimental at luminances lower than those used in the present study.[4] To explore this issue, measurements were repeated on one subject who viewed the display through a 3-mm artificial pupil to minimize optical effects. Values were compared to those made with the subject's natural pupil, but equated for retinal illuminance. A significantly greater reduction in vision with the larger (natural) pupil would indicate that optical factors mediate this effect. Although VA and SLCS were consistently better with the artificial pupil, the overall reduction in performance with decreasing retinal illuminance was about the same for artificial and natural pupils (Table 1), and the slope of this reduction also was comparable for the two conditions. Thus, for the range of luminances tested in the present study, the reduction in visual resolution cannot be attributed to optical factors.

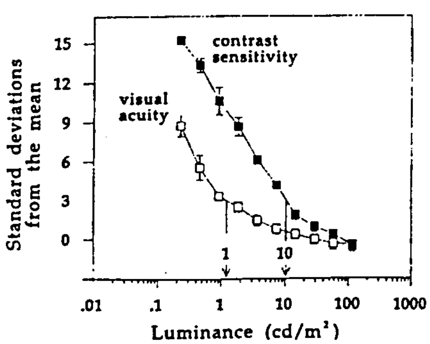

Figure 3. The average number of SD's from mean performance at maximum luminance (116 cd/m^2) is plotted against chart luminance for VA and SLCS.

DISCUSSION

The results of this study demonstrate that SLCS provides a sensitive index of changes in the luminance of the stimulus. Luminance reductions in the photopic range produced large losses in SLCS with minimal degradation of VA. Reducing the light level 100× (from 100 to 1 cd/m^2) produced an 8× reduction in SLCS, whereas VA remained normal by clinical standards [6/6 (20/20)].

It could be argued that comparison of VA and SLCS is not entirely valid because the two tests measure different aspects of visual function. Several approaches were used in this study, which mitigate against this criticism and facilitate comparison between acuity and contrast domains. First, by using letter charts of comparable design, with equal log steps of acuity and contrast, interval size and scoring were the same for the two measures. Second, small letters were used to assess both VA and SLCS, making it likely that thresholds were determined by comparable spatial frequency channels. Third, by standardizing all scores with respect to variability, VA and SLCS were expressed in equivalent units, making a more direct comparison possible. Despite greater variability, SLCS still proved to be a more sensitive index of changes in resolution with luminance.

The reduction in resolution observed with decreasing luminance could reflect optical factors such as pupillary dilation, aberrations, or inaccurate accommodation. However, previous research[4] and the results of our control experiment (Table 1) indicate that optical factors cannot explain the decline in VA and SLCS over the range of luminances tested. Hence this reduction apparently is linked to the decrease in retinal illuminance. It is noteworthy that SLCS varied in proportion to the square root of retinal illuminance, a finding which has been attributed to the quantal

TABLE 1. Decrease in visual performance with reduction in retinal illuminance.

Vision Test	Log Decrease in Visual Performance with Reduction in Retinal Illuminance (823–1.6 Td)	
	Natural pupil	Artificial pupil (3 mm)
Visual acuity	0.39 log units	0.36 log units
Contrast sensitivity	1.24 log units	1.18 log units

nature of light,[13, 14] and which has been reported for human and ideal observers limited only by photon noise.[6, 7, 14]

The greater reduction of SLCS than VA with decreasing luminance is of clinical interest because it suggests that SLCS is more sensitive to conditions that attenuate light to the central retina. Subtle visual reduction caused by light attenuation from early cataracts may be better detected, monitored, and correlated with symptoms by measuring SLCS. Diseases of the retina or optic nerve that reduce visual efficiency in a manner comparable to light attenuation also may be more readily detected by measuring resolution in the contrast domain. Further testing of SLCS in clinical populations is needed to validate these assumptions. We are currently developing a hard copy version of the small letter contrast test for widespread distribution.

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AUTHOR'S ADDRESS:
Jeff Rabin
Aircrew Health and Performance Division
U.S. Army Aeromedical Research Laboratory
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Fort Rucker, AL 36362

Dr. Garrison Rapmund
6 Burning Tree Court
Bethesda, MD 20817

Commandant, Royal Air Force
Institute of Aviation Medicine
Farnborough, Hampshire GU14 6SZ UK

Defense Technical Information
Cameron Station, Building 5
Alexandra, VA 22304-6145

Commander, U.S. Army Foreign Science
and Technology Center
AIFRTA (Davis)
220 7th Street, NE
Charlottesville, VA 22901-5396

Commander
Applied Technology Laboratory
USARTL-ATCOM
ATTN: Library, Building 401
Fort Eustis, VA 23604

Commander, U.S. Air Force
Development Test Center
101 West D Avenue, Suite 117
Eglin Air Force Base, FL 32542-5495

Aviation Medicine Clinic
TMC #22, SAAF
Fort Bragg, NC 28305

Dr. H. Dix Christensen
Bio-Medical Science Building, Room 753
Post Office Box 26901
Oklahoma City, OK 73190

Commander, U.S. Army Missile
Command
Redstone Scientific Information Center
ATTN: AMSMI-RD-CS-R
/ILL Documents
Redstone Arsenal, AL 35898

Aerospace Medicine Team
HQ ACC/SGST3
162 Dodd Boulevard, Suite 100
Langley Air Force Base,
VA 23665-1995

U.S. Army Research and Technology
Laboratories (AVSCOM)
Propulsion Laboratory MS 302-2
NASA Lewis Research Center
Cleveland, OH 44135

Commander
USAMRMC
ATTN: SGRD-ZC (COL John F. Glenn)
Fort Detrick, Frederick, MD 21702-5012

Dr. Eugene S. Channing
166 Baughman's Lane
Frederick, MD 21702-4083

U.S. Army Medical Department
and School
USAMRDALC Liaison
ATTN: HSMC-FR
Fort Sam Houston, TX 78234

NVESD
AMSEL-RD-NV-ASID-PST
(Attn: Trang Bui)
10221 Burbeck Road
Fort Belvior, VA 22060-5806

CA Av Med
HQ DAAC
Middle Wallop
Stockbridge, Hants S020 8DY UK

Dr. Christine Schlichting
Behavioral Sciences Department
Box 900, NAVUBASE NLON
Groton, CT 06349-5900

Commander
Aviation Applied Technology Directorate
ATTN: AMSAT-R-TV
Fort Eustis, VA 23604-5577

COL Yehezkel G. Caine, MD
Surgeon General, Israel Air Force
Aeromedical Center Library
P. O. Box 02166 I.D.F.
Israel

HQ ACC/DOHP
205 Dodd Boulevard, Suite 101
Langley Air Force Base,
VA 23665-2789

41st Rescue Squadron
41st RQS/SG
940 Range Road
Patrick Air Force Base,
FL 32925-5001

48th Rescue Squadron
48th RQS/SG
801 Dezonia Road
Holloman Air Force Base,
NM 88330-7715

HQ, AFOMA
ATTN: SGPA (Aerospace Medicine)
Bolling Air Force Base,
Washington, DC 20332-6128

ARNG Readiness Center
ATTN: NGB-AVN-OP
Arlington Hall Station
111 South George Mason Drive
Arlington, VA 22204-1382

35th Fighter Wing
35th FW/SG
PSC 1013
APO AE 09725-2055

66th Rescue Squadron
66th RQS/SG
4345 Tyndall Avenue
Nellis Air Force Base, NV 89191-6076

71st Rescue Squadron
71st RQS/SG
1139 Redstone Road
Patrick Air Force Base,
FL 32925-5000

Director
Aviation Research, Development
and Engineering Center
ATTN: AMSAT-R-Z
4300 Goodfellow Boulevard
St. Louis, MO 63120-1798

Commander
USAMRMC
ATTN: SGRD-ZB (COL C. Fred Tyner)
Fort Detrick, Frederick, MD 21702-5012

Commandant
U.S. Army Command and General Staff
College
ATTN: ATZL-SWS-L
Fort Levenworth, KS 66027-6900

ARNG Readiness Center
ATTN: NGB-AVN-OP
Arlington Hall Station
111 South George Mason Drive
Arlington, VA 22204-1382

Director
Army Personnel Research Establishment
Farnborough, Hants GU14 6SZ UK

Dr. A. Kornfield
895 Head Street
San Francisco, CA 94132-2813

ARNG Readiness Center
AATN: NGB-AVN-OP
Arlington Hall Station
111 South George Mason Drive
Arlington, VA 22204-1382

Mr. George T. Singley, III
Depupty Assistant Secretary of the Army
for Research and Technology
and Chief Scientist
ATTN: Room 3E374
103 Army Pentagon
Washington, DC 20310-0103

The Honorable Gilbert F. Decker
Assistant Secretary of the Army
for Research, Development,
and Acquisition
ATTN: Room 2E672
103 Army Pentagon
Washington, DC 20310-0103

Dr. Craig Dorman
Office of the Deputy Director,
Defense Research and Engineering
ATTN: Room 3D129LM
103 Army Pentagon
Washington, DC 20310-0103

HQ, AFOMA
ATTN; SGPA (Aerospace Medicine)
Bolling Air Force Base,
Washington, DC 20332-6188

Cdr, PERSCOM
ATTN: TAPC-PLA
200 Stovall Street, Rm 3N25
Alexandria, VA 22332-0413